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SURVEY OF LONG-TERM DURABILITY OF FIBERGLASS-REINFORCED PLASTIC STRUCTURES

S. Lieblein

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16. Abstract

A survey was conducted of available long-term strength properties of fiberglass-reinforced plastic structures. Included are fluid containment vessels, marine structures, and aircraft components with up to 19 years of service. Correlations were obtained for the variation of static fatigue strength, cyclic fatigue strength, and residual burst strength for pressure vessels. In addition, data were presented for the effects of moisture on strength retention. Data variations were analyzed, and relationships and implications for testing were discussed. Change in strength properties for complete structures was examined for indications of the effects of environmental conditions such as moisture and outdoor exposure (ultraviolet radiation, weathering) on long-term durability.

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by

Seymour Lieblein

SUMMARY

A survey has been conducted of the long-term strength properties of fiberglass-reinforced plastic structures. Included in the survey were data from fluid containment vessels, marine structures, and aircraft radomes with up to 19 years of service. Correlations were obtained for the variations of static fatigue strength, cyclic fatigue strength, and burst strength of pressure vessels. The relationship between static fatigue strength and residual burst strength was explored.

The effects of moisture on strength retention for both stressed and unstressed materials were examined, and implications for testing and design application were discussed. Strength retention for gasoline storage tanks after many years of service was documented and analyzed.

Examination of the change in strength properties with time for large-size composite structures indicated that the structures that were exposed to a high moisture environment in the absence of weathering and ultraviolet radiation could sustain their strength for long periods of time. However, when exposure to weathering and ultraviolet is present, appropriate surface protection appears to be required for long-term durability.

INTRODUCTION

Fiberglass-reinforced plastic has been used as a structural material for a wide range of applications in many fields of technology and construction. This composite material is also currently being considered as a potential candidate for the construction of low-cost blades for large wind power turbines (e.g., ref. 1). To achieve low overall cost, such blades must operate for a relatively long period of time (order of 30 yr) and for a relatively large number of rotational cycles (order of 10^8). The question of long-term durability of fiberglass-reinforced plastic structures, therefore, becomes an important consideration.

Long term durability (i.e., retention of strength properties with time) is a concern because of the potential degenerative effects of such exposure factors as atmospheric moisture and chemicals, ultraviolet radiation, and weathering (rain, hail, dust). These exposure factors can exist in conjunction with the customary strength degradation tendencies due to static (continuous load) and cyclic (fluctuating load) fatigue. A need exists, therefore, to identify the reaction of fiberglass materials to both exposure and fatigue effects for long periods of time and service conditions.

Fatigue strength of reinforced plastic materials is generally explored with laboratory tests of specimens in cycling machines. Test specimens are specially prepared or cut from the full structure. An example of fatigue results from an extensive test program on fiberglass laminates is given in reference 2. Such tests, however, cannot provide accurate information about the durability of the complete structure under actual operating conditions.

A useful general insight into the long-term behavior of fiberglass-reinforced plastic structures can be gained from examination of actual structures in real service over a long period of time. Such information is generally difficult to obtain, however, because of the required accurate documentation of the material properties and service history of the components. Furthermore, the likelihood of finding structures that have been in use for the time period of interest (30 yr) is rather remote. Nevertheless, there are several specific instances in the literature where complete structures are evaluated for real aging effects. Data are also available for complete structures tested under laboratory simulation of long-term effects. In all, results are in hand for structures in the general categories of fluid containment vessels, marine components, and aircraft components.

It is the purpose of this report to document the information available on the strength degradation of these complete fiberglass-reinforced structures. The scope includes identification of sources, tabulation and plotting of data, and correlation and analysis of results.

FLUID CONTAINMENT VESSELS

Data for time variations of strength properties are available for several types of filament-wound glass-reinforced plastic fluid containment vessels. These include high-pressure gas bottles, compressed-air tanks, and large-size gasoline storage tanks. Property evaluations were conducted for static (continuous load) fatigue, cyclic (fluctuating load) fatigue, and single-cycle burst strength. The effects of moisture were also examined. Data are presented from available literature and from unpublished tests conducted at the NASA-Lewis Research Center.

Small-Scale Vessel Fatigue Data

There are several references in the literature that deal with static or cyclic fatigue tests of small-scale filament-wound gas pressure vessels reported in the time period from 1961 to 1970 (refs. 3 through 7). The pressure vessels cited were constructed of fiberglass epoxy systems with E, S, or X glass. The pressure vessels considered were intended primarily for aerospace applications such as fluid containers or high-pressure pneumatic systems. Both laboratory and production samples were tested over a range of operating pressures.

The data presented in the reference permitted the development of correlations for static and cyclic fatigue for as-constructed, small size filament-wound pressure vessels. No exterior protective coating or paint was applied to these vessels. A summary of the data used, descriptions of the test specimens and test conditions, and the figures and tables in which the respective data appear, is given in table I. Data not specifically tabulated in several of the references are given in tables II and III.

A static fatigue point is obtained by pressurizing the vessel to a given operating pressure and maintaining that pressure with time until the vessel fails. A succession of such points at different pressure levels then defines the fatigue strength variation for the vessel (i.e., operating pressure against time to failure). A cyclic fatigue strength point is obtained by repeated cycling of the vessel pressure from zero to operating level (maximum value) to zero until failure occurs. The cyclic fatigue strength is then obtained from a number of such points at different operating pressure (i.e., operating pressure against number of cycles to failure).

Figure 1 shows the accumulated static fatigue data. Operating pressure is normalized with respect to initial ultimate pressure, designated by "percent ultimate" in the figure. Initial ultimate pressure, stress, or strength is defined as the average value for the first burstings of as-built, unstressed and unaged vessels. This terminology will be used throughout the report.

As indicated in figure 1, a reasonably well defined trend is apparent, despite the data scatter. Data scatter results not only from individual differences in response to aging, but also from the variability in initial ultimate strength values (e.g., around ±10 percent for ref. 7). Scatter in the short-time region can also be produced by differences in initial rate of pressurization, since the time of the 100 percent operating pressure point (initial ultimate strength) is taken as the time to reach peak pressure, t_0.

The correlation for room conditions was selected as shown by the dashed line in figure 1. Room test conditions are generally around 75° F and 50 percent relative humidity. Considerable uncertainty exists in the variation in the long-term region (1 to 10 yr). However, it appears that operating pressures no greater than 40 to 45 percent of the ultimate value are indicated for long-term freedom from static fatigue with these pressure vessels under room conditions.

The plotted results for cyclic fatigue are shown in figure 2. Here too, a correlation for room conditions can be readily established. Although the data are insufficient to extrapolate to the high cycle range (10^6 to 10^7), it does appear that a severe loss in strength could result for a high number of pressure cycles (order of 20 percent or less of ultimate pressure). In this regard, cycling appears to be a more severe factor in degrading tank strength than the time under continuous pressure. This can be seen from the consideration that for 2 to 60 cycles per minute, 10^6 cycles represents 3.3×10^3 to 10^5 hours. Within this time range, figure 1 indicates a higher allowable operating pressure than figure 2 for room conditions. Furthermore, for the few specimens that underwent both static and cyclic pressurizations there is no obvious indication that the respective static and cyclic fatigue strength losses are additive.

Small-Scale Vessel Burst Pressure Data

Data on the variation of burst pressure with time for small size filament-wound pressure vessels are available from some of the earlier references on fatigue tests (refs. 3, 4, and 6) and from an on-going test program conducted by James Faddoul at the NASA-Lewis Research Center. This program is based on a series of cylindrical tanks built by the Martin-Marietta Corporation for the Johnson Space Center (ref. 8). In the NASA-LeRC tests, tanks are periodically burst after varying lengths of aging.

The Martin-NASA tanks are lightweight, low cost pressure vessels intended for use as the portable storage tank for a fireman's compressed air-breathing system. Tank construction consisted of a load-sharing aluminum liner completely over-wrapped by a fiberglass/epoxy composite. Tank details are given in figure 3. No outer surface protective coating or paint was used. Internal volume is approximately 320 cubic inch.

A large number of the Martin-NASA tanks were installed in an outdoor pressurization farm as shown in figure 4. In this way, the effects of outdoor exposure on the durability of continuously-stressed, unprotected tanks could be investigated. Burst pressures were achieved in a burst pit through pressurization with hydraulic oil at a rate of around 1 minute to peak pressure.

Table IV presents a listing of the NASA burst results to date. Both unaged (for initial ultimate strength) and aged tanks were tested. In the case of the aged tanks with uncontrolled service, the precise service history is not known. The burst pressure data from the NASA tests are plotted in figure 5. As has been observed in other burst pressure tests (e.g., ref. 5), burst pressure is taken to vary linearly with age.

Figure 6 shows the same burst pressure data on a normalized basis, together with additional points from earlier references (table V). The estimated correlations for the two storage situations dramatically show the detrimental effect of outdoor exposure (i.e., ultraviolet radiation, moisture, and weather erosion) on the long-time strength of uncoated fiberglass vessels.

Burst Pressure and Static Fatigue

For a vessel in service at sustained operating pressure, the burst pressure variation with age is directly related to the static fatigue curve. Aged burst stress is basically a measure of the residual strength of the vessel after loading for a period of time at a given internal operating pressure. The relationship between burst strength and static fatigue strength is illustrated in figure 7. As shown in figure 7(a), the burst strength for a given operating pressure, or stress, is established by raising the internal pressure until bursting occurs after the vessel has been subjected to the operating load for varying periods of time. However, as time under load is increased, a point is reached where the vessel will burst without further increase in pressure, that is, the static fatigue point is reached (intersection with dot-dash curve).

As illustrated in figure 7(a), the two end points of the burst pressure curve for a given operating load are firmly established once the static fatigue strength is known. The variation between the end points appears to be approximately linear with time under load, as shown by the experimental data plot in figure 7(b), as well as figure 5(a). In figure 7(b), the burst strength is expressed in terms of calculated glass fiber stress instead of internal fluid pressure.

Indoor correlation. - With the establishment of the probable variation of burst pressure with age as illustrated in figure 7, it is possible to establish burst pressure curves for fiberglass pressure vessels for indoor conditions from the static fatigue correlation of figure 1. However, because of the uncertainty of the variation at long time under load, two extrapolations of the data of figure 1 are considered. If the tanks behaved close to a low extrapolation, as shown in figure 8(a), then burst pressures for low operating pressures ($\leq$40 percent of ultimate) would show little degradation with time. This seems to be the case with the indoor data in figure 6. Some burst data, however, show better comparison with the construction from a high extrapolation of the static fatigue curve, as shown in figure 8(b). In either case, the pronounced sensitivity of the burst pressure curves for long-time exposures to the variation of the static fatigue curve is clearly demonstrated in figure 8.

Outdoor correlation. - The use of a linear variation of burst pressure with time can also facilitate the estimation of the static fatigue curve for the outdoor exposure case. In figure 6, it is seen that the selected burst pressure curve for 35 percent ultimate pressure would intersect the operating pressure line (i.e., the static fatigue curve) at around 9.5 years. Transposition of this time value to a static fatigue plot then suggests an estimated variation as shown in figure 9. The figure clearly indicates the effect of outdoor exposure in reducing the static fatigue strength of uncoated fiberglass vessels. For long-term outdoor use (say, 10 to 30 yr), design operating pressures no greater than around 20 percent of ultimate appear to be indicated for such uncoated pressure vessels.

Burst pressure curves for outdoor storage can be constructed based on the assumed static fatigue curve of figure 9. Results are shown in figure 10. Here again, the indication for low operating pressures to avoid excessive burst strength degradation is apparent.

Test procedures. - The process of determining a point on the static fatigue curve from the extrapolation of the corresponding burst (residual) pressure curve, as illustrated in figures 6 and 9, might serve as a general alternative or complementary method to the customary test procedures for static fatigue strength. This approach might be particularly applicable for long time values (several years or more) where the static fatigue curve is very shallow. In this case, the combination of a very small curve slope and the usual scatter of the individual test points makes the accurate determination of the fatigue variation very difficult (e.g., fig. 1). Inasmuch as the slope of the burst pressure curve is much greater in magnitude than the slope of the static fatigue curve in this region, the effect of data scatter should be reduced. Furthermore, if the burst pressure variation is truly linear, then the test time can be reduced, since the end point can be determined by extrapolation.

Long-term strength degradation. - Another general application of the burst pressure curve concept lies in providing some insight into the probable degradation of residual strength with time for actual operating vessels. Service structures are generally designed for operating pressures well below the static fatigue strength for the design service life. Interest is thus directed toward examining residual (burst) strength variations for operating pressures below the design value of static fatigue strength.

As an example, it is desired to estimate the residual strength values for pressure vessels that are designed for a 20-year lifetime and that follow the static fatigue strength variations of figure 9. For the design life of 20 years, the fatigue strengths are around 50 and 33 percent, respectively, for indoor and outdoor conditions. Residual strength (burst pressure) curves can then be determined from the estimated values of fatigue strength at 20 and 100 years, as shown in figure 11. In this particular case, the curves indicate that little static strength degradation should occur even with small differences between operating stress and static fatigue strength.

From the example of figure 11, it can be concluded that in general, the greater the difference between design stress and fatigue strength, the less the residual strength degradation with service life. For particular designs, a substantial margin between design stress and fatigue strength is generally used because of the uncertainty and variability of the fatigue strength variation, especially for long design life. This procedure tends to promote small strength degradation. However, if a vessel is required to operate at relatively high stress levels for long periods of time, it is important that an accurate determination of fatigue strength be made.

Effects of High Moisture Environment

One of the environmental factors that is known to affect the long-term strength properties of fiberglass-reinforced plastic structures is exposure to water or moist air (high humidity). This effect depends on the particular resin system and fiberglass finish of the material, as well as on the temperature of the exposure. There are a number of investigations that have explored the effects of water exposure on fluid containment vessels. These investigations were conducted by immersing the material samples in a container or chamber which maintains the water or moist air at a constant temperature and relative humidity. Data are available for pressure vessels under operating conditions, unpressurized vessels, and laminates for petroleum storage tanks.

Pressurized vessels. - Reference 3 contains several results for the static and cyclic fatigue strength of small filament-wound pressure vessels tested under high moisture conditions (95 percent relative humidity) at elevated temperatures. Fatigue tests were conducted with small (300 cu in.) spheroidal tanks used in military aircraft service. Results are listed in tables VI and VII.

Table VI shows the effect of service history prior to test pressurization for uncoated fiberglass tanks. The effects of age, flight time, temperature, and relative humidity on both static and cyclic fatigue were found to be quite pronounced for these early uncoated tanks. However, a change in the type of fiber sizing and the addition of a protective coating (as available at the time of the tests) to reduce moisture penetration were effective in improving the fatigue strength of new tanks, as shown in table VII.

Figure 12 presents the data for static fatigue strength at 95 percent relative humidity compared to the room conditions variation as obtained from the correlation of figure 1 and an initial ultimate pressure value of 7020 psi. This value was established from the mention in the reference that 3000 and 4000 psi were 45 and 60 percent, respectively, of the minimum initial burst pressure. The selected initial ultimate value was then obtained from the consideration that the correlation represents an average value and the assumption of ±5 percent variability in the initial data values.

The plot of figure 12 clearly indicates the impact of fiberglass finish, temperature, and age prior to exposure on static fatigue strength. The corresponding impact on cyclic fatigue is shown in figure 13, as compared to the room temperature value obtained from figure 2. These figures also indicate the potential for minimizing the moisture effect with proper material formulation and treatment.

Elevated humidity and temperature appear to have independent effects on the strength degradation for a given material. It is speculated, for example, that a normalized static fatigue curve for a fiberglass material exposed to elevated humidity and temperature might be synthesized as shown schematically in figure 14. Figure 14(a) shows the as-measured trend of variation. With temperature increase, the curve is displaced downward because initial ultimate strength declines with increasing temperature.

The key aspect of the situation is the decrease in ultimate (unstressed) strength with time under exposure, with trends for humidity and temperature as shown in figure 14(b). If measured pressures at failure were then normalized on the basis of the local ultimate pressure instead of the initial ultimate value, a reduced spread of the variations might be observed as shown in figure 14(c).

Unstressed vessels. - There are some data available on the effects of a high moisture/elevated temperature environment on the ultimate strength of small unpressurizied filament-wound vessels. Reference 9 reports results of burst pressure tests of small S-glass/epoxy pressure vessels exposed to a 140° F, 95 percent relative humidity environment for several periods of time up to 16 weeks.

The composite material used S-2-glass rovings with an epoxy compatible finish. The epoxy resin system was Epotuf 37-139, Epotuf 37-624, EMI-24, and UCCAA 1100 in the ratios 100/84/2/1.6, respectively. Resin content was not given. The cure schedule was 1½ hr at 275° F, 1 hour at 325° F, and 1 hour at 400° F. The pressure vessel specimen was configured with a nominal inside diameter of 3 inches, a cylindrical length of 5 inches, and integral geodesic isotensoid domes on each end. Wall thickness was not noted. Wet filament winding was used in the construction of the vessels.

The test program involved 12 test points with 16 vessels per sample point. This sample size was chosen so that statistically reliable distributions could be obtained. An environmental chamber provided a 140° F, 95 percent relative humidity exposure for 2, 6, and 16 weeks for the unpressurized sample. Burst pressurization after exposure was conducted at room temperature. Pressurization rate to burst was 250 psi per second with water as the pressurizing medium. The loading and vessel construction was such that a hoop type failure resulted.

The first part of the program determined the burst pressure variation (ultimate strength) of the as-built virgin specimens. The second set of tests examined the effect of proof pressure testing of the sample prior to exposure. The proof pressure test consisted of pressurizing an as-built vessel to 75 percent of the mean burst strength (2980 psi). The final tests involved samples encased in a 0.040-inch thick fiberglass cylinder, or painted with a phenolic paint primer. The purpose of these additions was to reduce moisture penetration.

Results of the burst pressure tests after environmental exposure are listed in table VIII and plotted in figure 15. For the as-built (virgin) vessels, the loss in burst pressure strength is most pronounced initially, but then appears to taper off, with a strength reduction of around 30 percent at the 16-week time. When the pressure vessels were subjected to the proof test prior to moisture exposure, there was a further decrease in burst pressure (around 10 percent). It is believed that the proof test cycle develops some crazing of the material, which tends to increase moisture penetration. Figure 15 also shows that for the materials involved, the use of a sealed tube or painted surface had relatively little effect in reducing the strength degradation of the vessels. Apparently, these methods did not provide an effective barrier to moisture penetration.

The further drop in residual strength observed for the case of the single proof test cycle in figure 15 may provide some insight of the behavior of the vessel under stress. It is likely that static and cyclic fatigue strengths of this particular laminate formulation might degrade considerably under conditions of high humidity and elevated temperature at service operating pressures.

Fuel tank laminates. - Data are available for the variation of strength retention with time for three unstressed laminates immersed in water. These laminates, composed of various types of polyester resins, were representative of fiberglass formulation for chemical and petroleum fuel storage tanks. Water temperature was at the room level except for one series which was held at 100° F for the first 4 years. Laminate thickness was from 0.125 to 0.2 inch. Results of strength tests conducted after immersion, as reported in references 10 and 11, are shown in figure 16.

The most striking feature of figure 16 is the large variation in strength retention with chemical formulation for the polyester resins. The variation also reflects the progress with time in developing resin systems with low moisture penetration. The lowest curve was for laminates constructed around 1948 from cloth treated with a poor finish. They were press molded to a high glass content with unsealed edges, conditions which are not favorable for good moisture resistance. The middle curve was obtained from an early bisphenol polyester resin formulation constructed around 1954. Two sources of data (the symbol point and the dashed line) were available for this material. These specimens contained 45 to 50 percent glass and they, too, did not have a surfacing veil or sealed edges. The highest curve was obtained from samples cut from storage tanks that were constructed around 1965 based on a high molecular weight isophthalic polyester resin with reinforcements developed for compatibility with the resin.

In all cases, it appears that most of the strength loss occurs within around the first year of exposure. A rapid loss also appears to be the case for the small pressure vessel exposed to high moisture air, as was shown in figure 15. This trend may reflect some form of water saturation condition for the laminates, where continued exposure does not lead to a progressive decline in strength.

It should be noted that a stepped variation was introduced for the data of the upper curve in figure 16 as a possible reflection of a temperature effect. Air temperature was seen to be a large factor in the fatigue strength of pressurized bottles at high humidity (figs. 12 and 13). It is reasonable, therefore, to consider that water temperature also affects the strength retention of unstressed materials immersed in the liquid.

Laminates at elevated temperature. - Reference 11 presents results of an investigation of glass/polyester resin laminates for corrosion resistance in chemical tank applications. Included are results for laminates immersed in water at room and near-boiling temperatures. The laminates were made from hydrogenated bisphenol-A polyester resin by land lay-up. Glass content was 25 to 30 percent in mat form. The laminates were veiled with a chemical type glass mat and had edges sealed with resin to minimize wicking. Flexural strength was determined after immersion in water for up to 12 months. The specimens exposed to elevated temperature were tested in boiling water.

The results of the tests are shown in figure 17(a). A substantial decrease in flexural strength is observed from room to boiling temperature, with nearly parallel variations. As in the case of figures 15 and 16, the decline in strength with exposure time becomes about constant within a year. The ratio of strengths from 210° F to room temperature ($\sim$75° F) is 0.66 for zero exposure time (initial ultimate strength), and 0.55 for the essentially constant variation at 12 months and beyond. This latter ratio and the specimen strength ratio between 75° and 100° from the upper curve of figure 16 can then be used to form a possible estimate for the temperature effect on long-term ($\geq$1 yr) ultimate strength for polyester resin laminates in water. These values form a nearly linear correlation as shown in figure 17(b). However, the variation shown may be valid only for the materials used; more data are needed to confirm the trend.

Test implications. - The observation that most of the strength decline of materials immersed in water or moist air occurs within about the first year (figs. 14 and 15) may have some useful implications for testing for long-term durability. The first use could be for screening of material formulations and constructions for resistance to moisture penetration. It is possible that an adequate comparative evaluation might be apparent in as little as say 6 months. In this regard, if the observed variation in strength retention is indeed some form of saturation effect, it is conceivable that the thickness of the test specimen may have an effect on the time at which the curve leveling occurs. It would be of interest to determine whether a thin specimen would attain the minimum level in a shorter period of time than a corresponding thick specimen.

A second use of short term ($\sim$6 mo) immersion tests could be for obtaining parametric data for correlations of strength retention as a continuous function of varying degrees of moisture level and temperature. The intent would be to expand the type of data and correlation shown in figure 17 to more values of temperature and relative humidity for applicable material formulations. There could be several potential applications of such correlations in fiberglass material testing and design.

A first application might involve situations, such as for wind turbine blades, where there are relatively large variations in environmental temperature and relative humidity with time. If such variations can be estimated from climate data, then some form of average or effective environmental effect on material ultimate strength can be determined from the immersion data correlations.

Moisture/temperature correlations for ultimate strength may also be of use in estimating long-term fatigue strength. Again, for applications such as wind turbine blades, the material is subjected to varying stress levels as well as varying environmental conditions. Testing for long-term cyclic fatigue (order of 10^7 cycles) is a costly and time-consuming process, especially when many variables are considered. As a result, most testing is done at room conditions. It may be possible to combine the room-condition cyclic fatigue variation with the correlations for ultimate (no-load) strength retention, as outlined above, to provide some estimate or synthesis of the fatigue life in the actual environment of varying temperature and humidity. An example of such a procedure was given in figure 14 for static fatigue strength.

Underground Gasoline Storage Tank

A large number of early fiberglass-reinforced plastic tanks were constructed in the 1960's for the underground storage of gasoline. The tanks were filament wound with E-glass and high molecular weight isophthalic polyester resin and with a C-glass interior surface veil. The type of resin used provided a good barrier to both water and gasoline. Overall dimensions were of the order of 8 feet in diameter by 20 feet in length with a 0.2 inch wall thickness. Two of the underground tanks were unearthed after different times of service, and pieces were removed for determination of flexural strength properties.

Tank after nearly 7 years. - The first tank, installed in Houston, Texas, was removed in 1971 after 6 years and 10 months of service (ref. 12). The tank was sectioned for observation of the interior, and a section was cut from the tank wall on the bottom for measurement of material properties. Analysis of the bedding material under the tank indicated a pH of 9.75, and a soil resistivity of 800 to 2000 ohms.

Visual inspection revealed the tank to be in excellent condition. There was no evidence of crazing or cracking of the inner surface. Only a staining of the inner surface from gasoline colorants was found. The outer surface was similarly without any signs of attack. There was, however, a light chalking (due to long-term exposure to moisture) which was easily scrubbed off.

A comparison of measured flexural properties of the sample cut from the tank with original values is shown in table IX(a). Considering that the aged properties are single values compared to average values for the original properties, the measured changes are not statistically significant. Mechanical properties appear to be effectively unchanged after the time of exposure.

Tank after nearly 13 years. - The second tank, which was installed in Stony Ridge, Ohio, was removed in 1977 after 12 years and 9 months of continuous service (ref. 13). A photograph of the tank after removal is shown in figure 18. The exterior surface of the tank ends and the center joints had a white, somewhat chalky film, which easily scrubbed off with an abrasive cleaner. This surface effect was typical of air-cured fiberglass surfaces exposed to moisture over long periods of time. No areas of cracking or crazing were found on the inner surface.

A section was cut from the tank wall on the side, and flexural properties and hardness were measured (five samples for each measurement). Average results from reference 13 are shown in table IX(b). Effectively, there was no significant change in properties over the nearly 13 year time period. Small decreases were observed only for the flexural modulus and the Barcol hardness.

Evaluation. - The above results of essentially no change in flexural strength with time for the underground storage tanks can be interpreted in light of previous discussions. First, gasoline storage tanks are vented, and therefore, are not subject to internal fluid pressure. The structure can thus be considered as essentially unstressed. Also, an underground tank is not exposed to ultraviolet radiation or weather erosion. However, there is contact on the outside with moisture from the surrounding soil, and on the inside with the fluid content. Therefore, the tank wall can be regarded as an unstressed material immersed in water and gasoline.

Data for strength retention of laminates of tank material immersed in water and in gasoline are given in reference 10 and plotted in figure 19(a). The curve for water is the same as in figure 16 with the added conjectured temperature effect. A step rise is also shown for the gasoline, since its temperature, too, was reduced from 100° to 75° F after 4 years. However, this curve is somewhat uncertain because of the large difference between the values at 2 and 6 years. For the service tank situation, an estimated variation was taken as the average of these two curves.

The estimated strength retention variation for the tank material laminate at 75° F is shown in figure 19(b), together with the values for the actual in-service tanks as obtained from the data of table IX. The laminate data suggests little strength loss to 13 years, with an estimated strength retention of around 92 percent for liquids at 75° F. The actual tank results show effectively a 100 percent strength retention. However, considering that average underground soil temperatures are most likely lower than 75° F, the comparison is very good. Laminate immersion tests thus appear to be an effective means for determining the water/moisture resistance of unstressed (and perhaps lightly stressed) fiberglass formulations in actual service.

In a second interpretation of the gasoline tank data, it is noted that although the tanks are vented, steady wall stresses are generated by the weight of the gasoline contents and the surrounding soil. Thus, the tanks can be regarded as pressure vessels under sustained load. As such, they will have static fatigue and residual (burst) strength variations similar to those discussed previously for the small-size pressure vessels. A residual strength plot will now be estimated for the gasoline tanks.

Specific static fatigue data for the glass/polyester resin system of the gasoline tanks (similar to fig. 1 for predominately epoxy resin systems) are unavailable to the author. Polyester resin systems generally have lower strength than epoxy resin systems, but it is not known whether the static fatigue strength will also be lower on a percent of ultimate basis. If it is assumed that the static fatigue ratio for polyester resins is around 10 percent lower than the room-conditions correlation of figure 1 at 10 years, and if a further 10 percent reduction is taken for the water/gasoline exposure, then an estimated static fatigue strength variation can be established as shown by the solid curve in figure 20(a). A further reduction is then taken for conservatism as shown by the dot-dash curve in figure 20(a). This range of values can then be used to determine the sensitivity of residual strength results to the selection of the static fatigue variation.

The residual strength plot for the selected static fatigue curves of figure 20(a) is shown in figure 20(b). This plot was constructed, as was done earlier in the report, by drawing straight lines to the corresponding percent stress points on the static fatigue curves. According to the results of figure 20(b), strength retention for the gasoline tanks should be greater than 90 percent for values of operating stress below between 30 to 37 percent of the initial ultimate strength value. According to the manufacturer, the tanks were designed for a factor of safety of five. Thus, the ratio of maximum steady stress in the tank wall to the ultimate strength of the structure was around 0.2. A 20 percent operating stress level falls well above residual stress values shown in figure 20(b). Thus, if the gasoline tanks behaved as pressure vessels, there should be very little decrease in residual strength for the indicated service times, as is observed by the measured data.

MARINE STRUCTURES

Fiberglass laminates have been used for many years in both commercial and naval marine vessels because of their durability under long-term exposure to salt air and water. Application in the former category include pleasure, fishing, work, and charter boats, lifeboats, and hatch covers. Naval uses include patrol boats, mine-sweepers, and submarine fairwaters (coning towers). Results are available in the literature for investigations of laminate strength properties after extended service time for a Coast Guard patrol boat and a Navy submarine. For these structures, the environmental exposure is immersion in sea water or contact with moist, salty air.

Patrol Boat

Forty-foot fiberglass-reinforced plastic patrol boats (fig. 21) were built for the Coast Guard during the early 1950's. The structural configuration consisted of a single skin fiberglass-reinforced plastic hull and cabin. The fiberglass laminates in the hull were fabricated with 10-ounce cloth mat and $1\frac{1}{2}$-ounce chopped strand reinforcements. Materials were E glass and general purpose polyester resin. Average laminate thickness was around 3/4 inch for the bottom shell, and around 3/8 inch for the side shell, deck, and cabin.

In 1962, after 10 years of service, three of the 40-foot patrol boats were examined, and a laboratory analysis was made of samples cut from the hulls. Since the boats were still in service, a single relatively small panel (12 in. x 12 in.) was removed for samples. Further hull samples were taken from one of these boats, CG40503, in the spring of 1971 upon its retirement after almost 20 years of service. Larger panels from two locations on the hull bottom were removed for samples. Average thickness was 0.682 inch compared to 0.875 inch for the 1962 samples. Testing was conducted in 1972.

A comparative study of similar tests from these two samplings conducted in 1962 and 1972 is described in reference 14. Visual examination of the removed panels showed no evidence of deterioration due to age or environment (fig. 22). There was no discoloration beyond the first millimeter of thickness, and there was no indication of water or other contaminants penetrating the small number of voids in the laminate.

Results of the mechanical property determinations are shown in table X. Comparison indicates that there was no significant deterioration of strength over the previous 10 years. The apparent increases in flexural and tensile strength are more likely attributed to sampling error, since only one specimen could be cut from the 1962 sample.

Barcol hardness readings were not recorded for the bottom hull in 1962 because of the irregular surface conditions of the laminate. However, the inner and outer surfaces of the 1972 hull panels were tested for Barcol hardness. Results compared well with the readings made of the side shell and cabin laminates in 1962. Specific gravity data, as well as the Barcol comparison tended to substantiate the conclusion of the visual examination that water and other chemical reactants did not penetrate the laminates.

The design safety factor for the patrol boat hull was indicated in reference 10 to be such that the mean stress was kept below the long-term static fatigue strength limit. This limit was mentioned as 20 to 25 percent of the ultimate strength. The design life of the boat was not specifically stated either. However, inasmuch as the boat had almost 20 years of active service, the design life must have been longer. The design operating stress for the structure is thus judged to be less than 20 percent ultimate at 25 to 30 years. If the static fatigue variation for the hull laminate was close to that for the filament-wound pressure vessels (fig. 9), then very little residual strength degradation would be anticipated. However, since the static fatigue strength for the hull laminate is not known, a firm analysis cannot be made to support the observed data.

Submarine Fairwater

Data are also available for the effect of extended service on the properties of a large fiberglass-reinforced structure, the fairwater on the submarine U.S.S. Halfbeak (ref. 15). The use of glass-reinforced plastics for this component of the vessel was considered because of continuing operational difficulties with aluminum fairwaters, principally due to electrolytic corrosion and maintenance problems.

The submarine fairwater, sketched in figure 23(a), was constructed of Style 181-Volan glass cloth, which is a high-strength satin weave, bidirectional textile treated with a special finish to improve resin bond and water resistance. The plastic matrix was a general purpose polyester resin, blended with 10 percent of a flexible resin for added toughness, and formulated for room-temperature curing. A vacuum-bag molding process was used to assure low void and high glass content.

The elements of the fairwater were shop assembled and installed aboard the "Halfbeak" in late 1953, and the structure entered into service in early 1954. In early 1965, the plastic fairwater was removed from the vessel after 11 years of service. Following removal, two curved panels approximately 27 inches by 49 inches were taken from the structure for testing.

Test specimens were prepared from each of the sample panels, and properties were determined by pertinent methods for this type of laminate. Results are shown in table XI, together with corresponding property determinations for the original material. The "wet" condition was intended to simulate the effects of extended immersion in water at normal temperatures. The Barcol hardness was used as a measure of the degree and adequacy of the resin cure.

On an overall basis, the data of table XI indicate relatively small changes in mechanical properties of the laminate panels after 11 years of service. The most substantial change appears in the wet flexural strength (average decrease of 14 percent), although the original increase in strength for the "wet" condition appears unusual. In all cases, the properties after 11 years still met the design specification requirements.

Reference 15 mentioned that in terms of stress in the material, final design analysis indicated a safety factor of four in the laminate. Thus, operating stress levels were probably less than 25 percent of ultimate. For such values, a situation similar to that for the previous fiberglass boat hull is probably in effect. Thus, relatively small reductions in residual strength would be expected.

Reference 15 also referred to sea-water immersion tests of then current glass-reinforced plastic materials. After a 5-year immersion period, the Style 181 cloth laminate retained over 95 percent of original strength and stiffness. Additional comment was made of weather-aging investigations of such laminates. In general, the properties of properly fabricated glass-reinforced plastic materials were not affected seriously by long-term exposure to weather. Treatment with standard vinyl-alkyd paint systems was effective in protecting the substrate resin from erosion.

As a final indication of the long-term durability of glass-reinforced-plastics in marine service, the paper mentioned the installation of 25 newly-designed glass-reinforced-plastic fairwaters on Guppy-class submarines. A sketch of this type of fairwater is shown in figure 23(b).

AIRCRAFT STRUCTURES

Data are available on the strength degradation of two fiberglass composite structures after aging under years of real life exposure in aircraft service. The structures are radomes on the Grumman E-2A and A-6 aircraft (ref. 16). These parts were exposed to a variety of extreme climactic conditions under actual flying loads. Thus, they were subjected to weathering erosion and ultraviolet and moisture exposure, and can show the protective values of paint coatings.

E-2A Rotodome

The rotodome of this aircraft, shown in figure 24, is a fiberglass/epoxy structure consisting of two sandwich type skins of 2 to 18 plies thick over an inner rib structure. The skin laminate was made from 181 style fiberglass fabric with Volan A finish impregnated with Shell Epon 828 resin with CL hardener. The skin was cured on steam heated steel molds with additional radiant heat from above. The leading edge was painted with rain erosion coating, and the remainder of the rotodome was covered with epoxy aircraft paint. Fabrication was in 1959.

The unit was installed on a test aircraft in 1960 and flown for several years. After completion of the test flights, the rotodome was removed and stored outdoors where it was subject to various atmospheric conditions common to Long Island, New York. It was retrieved from storage in 1978 (19 yr after its fabrication) and inspected. Flat sections were cut from various areas and machined into tensile and flexural specimens. Specimens were taken from areas where the paint adhesion broke down and where the paint remained intact.

Tensile and flexural tests were performed on the rotodome samples, and the data were normalized using 0.011 inch per ply as the nominal thickness. The original strength of the structure was determined from polar property curves of the material in conjunction with measured orientations of the various plies in the laminate. The sum of the strengths of each ply, based on 0.011 inch per ply thickness, was assumed to be the original strength of each specimen.

Results of the strength tests are given in table XII. Inspection of the listings reveals the following observations. The bottom skin, which experienced little exposure to ultraviolet radiation, showed the least indication of any degradation. This was followed by the upper and inner skin areas, which showed a modest strength degradation ($\leq$10 percent). There was no marked difference attributable to the paint on or off condition for the upper skin (probably depends on the relative time and extent of paint loss - values not recorded). Decrease in modulus varied from around 7 percent for the bottom skin to from 5 to 28 percent for the upper and inner skins. The cap, which was heavily eroded (with complete loss of coating), showed the largest degradation (32 percent loss in flexural strength). These results, as well as those discussed previously for the NASA burst tests, strongly indicate the potential vulnerability of unprotected fiberglass structures to ultraviolet radiation and weathering.

It should be noted, that the rotodome was subjected to actual flight loads for only a small part of the total elapsed time. Also, the surface coatings were not maintained after the structure was placed in storage. The reported results may, therefore, not necessarily be the same as would occur for 19 years of full service and maintenance.

A-6 Radome

A second well-documented aircraft structure (ref. 16) is the nose radome on the Grumman A-6 aircraft (fig. 25). This radome was fabricated by a modified fiberglass filament winding process which consisted of an alternate winding of circular and longitudinal fibers. The resin formulation originally used (1963) was Shell Epon 828 epoxy resin with BF_3-400 hardener. However, when it was determined that this hardener was somewhat hygroscopic, the formulation was changed to the same epoxy resin but the MNA-BDMA curing agent/hardener combination ($\geq$1965). Rain erosion coating was applied to the outer surface and maintained during the service life of the unit.

Five radomes on service aircraft were removed for modification after 11 to 15 years under varied combat and service environments. Test specimens were cut from a removed portion of the radome and subjected to property tests (ref. 25). Polar-plot strength values were available for both hardeners, so that determination of original properties could be made.

Results of the tensile and flexural tests are shown in table XIII. For the four units with the improved hardener, the tension, flexure, and stiffness measurements showed no average reductions for 10 to 13 years of exposure. The protective rain erosion coating on the radome outer surface was apparently very effective against aging and degradation.

CONCLUDING CORRELATIONS

The comparative static strengths for the available complete structures can provide a composite graphic view of the effect of aging on full-scale fiberglass-reinforced structures. Data for static strength degradation of complete structures have been presented herein for a gasoline storage tank, a patrol boat, a submarine fairwater, an aircraft rotodome, and an aircraft radome. Values of percent change in strength and modulus over the test time period were determined for these structures (except for the highly eroded rotodome cap) and plotted in figure 26.

It is clear from the strength change values in figure 26(a) that there is considerable scatter in the data (maximum reduction, 14 percent), and that there is no apparent major trend of variation within this scatter. Considerable scatter is also observed for the modulus change in figure 26(b). However, it does appear that there could be an average reduction in modulus over the time period covered. An average value from the modulus data presented might be of the order of -10 percent after 20 years. The overall observation suggested from these plots, however, is that material static strength in fiberglass structures can be retained for a considerable period of time under real service conditions.

More specifically, it is noted that the underground gasoline storage tank, the patrol boat hull, and the submarine fairwater have a number of conditions in common: high moisture environment; no surface coating; and no or partial exposure to ultraviolet radiation and weathering. This combination of conditions, as was speculated in earlier analysis, does not appear to pose a serious problem and can sustain high levels of residual strength, providing the operating stresses are relatively light. It should also be noted that the service areas for these structures did not involve elevated temperatures (probably in range from freezing to around 75° F). On the other hand, structures which are continuously exposed to ultraviolet radiation and weathering, such an aircraft components, appear to require appropriate surface protection to retain their strength properties for long periods of time.

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TABLE I. - SUMMARY OF DATA SOURCES FOR FATIGUE STRENGTH CORRELATIONS FOR FILAMENT-WOUND PRESSURE VESSELS

Reference	Type of data	Vessel description	Test conditions	Table	Figure
5 (1964)	Static fatigue: faired variations from data in reference[a]	8-in. diam ovaloid. Two sets, epoxy resin with rovings of E-HTS glass and X-944 glass. Cure, 24 hr at 250° F; laboratory samples.	Time to reach pressure, 1 sec. Room conditions		1
4 (1961)	Static fatigue, cyclic fatigue, burst pressure: individual points. Curve variation for static fatigue.	Air bottles; materials not specified. 870 cu in. and smaller. Production samples. Designed for 3000 psi and 10 000 hr life	Hydrostatic pressurization, 2 to 5 cycles per minute. Room conditions	II, V	1,2,6,8
3 (1962)	Static fatigue, cyclic fatigue, and burst pressure: individual points	Fiberglass; oil and starch sizing. 300 cu in. spherical vessels for aircraft service	Pressurization rate, 2500 psi/min; cyclic rate, 2 to 5/min. Room and elevated temperature and humidity	III, V, VI, VII	2, 12, 13
6 (1967)	Static fatigue and burst pressure: single point	Cylindrical laboratory samples, 7½ in. I.D. by 20 in. S-994/HTS/epoxy prepreg tape.	Gaseous helium and water pressurization, 250 psi/min. Room conditions	V	1, 8
7 (1970)	Static fatigue and cyclic fatigue: individual points	Cylinders, 7½ in. I.D. by 20 in. S/901 glass and epoxy resin, polyimide internal liner. Laboratory samples, 707 cu in.	Oil pressurization, 15 sec to reach pressure. Room conditions	III	1,2

[a]E-glass data refaired compared to line in reference - now coincident with X-944 glass on percent ultimate basis.

TABLE II. - FATIGUE DATA FOR FILAMENT-WOUND FIBERGLASS AIR BOTTLES. DATA FROM REFERENCE 4. ROOM CONDITIONS

Vessel number	Test condition	Pressure, percent ultimate	Time to failure, hr	Pressure cycles to failure
1	Static fatigue	62.5	9.51×10^2	
2		50.5	1.79×10^3	
3		50	3.65×10^3+	
4		44	3.65×10^3+	
5		39	8.76×10^4+	
6		39	8.76×10^4+	
7		39	1.82×10^4+	
8		37	1.93×10^4+	
9	↓	61	1.17×10^4+	
10	Cyclic fatigue, 25 months at 2900 psi before cycling 0 to 3000 psi	[a]38		8.70×10^3

[a]Based on ultimate strength of 7900 psi.
+Terminated, without failure.

TABLE III - FATIGUE DATA FOR FILAMENT-WOUND

FIBERGLASS-REINFORCED PRESSURE VESSELS

FROM REFERENCES. ROOM CONDITIONS

(a) Cyclic fatigue, ref. 3, fig. 1.
300 cu in. spherical vessels

Pressure, percent ultimate	Pressure cycles to failure
86.5	4.5
72.5	7.0x10
54	1.7×10^3
48	3.0×10^3
38	4.1×10^4
32	7.0×10^4
22	3.5×10^5+

\+ Terminated, without failure.

(b) Cyclic and static fatigue, ref. 7, figs. 2 and 3.
707 cu in. lined cylindrical vessels, S-glass/epoxy

Cyclic fatigue		Static fatigue	
Pressure, percent ultimate	Pressure cycles to failure	Pressure, percent ultimate	Time to failure, hr
80	3.4x10	90	1.15×10^{-1}
80	3.9x10	80	1.57
80	4.2x10	80	2.02
80	4.6x10	80	3.50
70	1.08×10^2	80	7.33
70	1.5×10^2	80	1.42x10
65	2.5×10^2	70	2.33
60	3.25×10^2	70	1.07×10^2
		60	2.17x10
		60	5.03x10
		60	9.33x10

TABLE IV. - BURST TEST DATA FOR UNCOATED FIBERGLASS REINFORCED STORAGE TANKS FORMED BY S-GLASS/EPOXY OVERWRAP ON ALUMINUM LINER (MARTIN-MARIETTA, REF. 8)

[Unpublished NASA-LeRC tests.]

(a) Unaged[a] tanks

Tank number	Service history	Burst pressure,[b] psi
1	Fire department use[c]	13 340
2	Fire department use[c]	13 240
3	Fire department use[c]	13 250
4	1000 cycles, 0 to 4500 psi	13 100
5	1000 cycles, 0 to 4500 psi	10 700

[a]Outdoor exposure of several weeks or less.
[b]Representative initial ultimate burst strength taken as 13 000 psi.
[c]Stored indoors unpressurized for several months prior to test.

(b) Aged tanks

Tank number	Service history				Burst pressure, psi
	Pressure,[a] psi	Number of cycles	Location	Number of years	
1	4500	----	Outdoors	1	10 600
2	4500	----	Outdoors	2	11 800
3	4500	----	Outdoors	3	10 000
4	4500	----	Outdoors	4.1	9 100
5	4500	----	Outdoors	4.34	8 300
6	4500	----	Outdoors	5	6 600
7	4500	----	Outdoors	6	9 400
8	4500	2000[b]	Outdoors	2	10 500
9	4500	3000[c]	Outdoors	4	11 400
10	4500	3000[c]	Outdoors	4.5	(d)
11	4500	5000[c]	Outdoors	6	8 700
12	0	----	Outdoors	3	9 200
13	0	----	Outdoors	4	10 250
14	0	----	Outdoors	6	10 200
15	0[e]	----	Indoors	5	12 550
16	0[e]	----	Indoors	5	9 800

[a]Continuous.
[b]Cycled from 0 to 4500 psi before test.
[c]Cycled 1000 times from 0 to 4500 psi after 2nd, 3rd, and 4th years.
[d]Liner leakage at 4500 psi.
[e]Uncontrolled service; no records, but few pressurizations.

TABLE V. - BURST PRESSURE DATA FOR FILAMENT-WOUND PRESSURE VESSELS FROM REFERENCES. ROOM CONDITIONS

Reference	Operating pressure		Time, yr	Burst pressure	
	psi	Percent ultimate		psi	Percent ultimate
4	2900	36.7	2.21[a]	7300	92.4
	4800	60.8	1.33[a]	7300	92.4
3	3000	45	3.33[b]	8000	100
6	500	64	.092	716	92.5

[a]Cycled 1068 times at 38 percent of ultimate before burst.
[b]Includes 400 hr flight service.

TABLE VI. - EFFECT OF SERVICE HISTORY ON FATIGUE OF

UNCOATED FILAMENT-WOUND FIBERGLASS PRESSURE VESSELS

[Data from ref. 3. Spherical tanks in aircraft service.]

(a) Static fatigue strength

Age, months	Flight time, hr	Temperature, °F	Relative humidity, percent	Pressure,[a] psi	Time to failure, hr
New	0	160	95	3000[b]	158
36	0	160	95	3000	21
40	502	160	95	3000	9

(b) Cyclic fatigue strength

Age, months	Flight time, hr	Temperature, °F	Relative humidity, percent	Pressure,[c] psi	Cycles to failure
New	0	75	50	3000[b]	20 000+
40	400	75	50	3000	20 000+
New	0	100	95	3000	1 600
42	334	100	95	3000	1 510
New	0	160	95	3000	1 000
36	0	160	95	3000	841

[a]Vessel maintained under pressure until failure; cycled from pressure to zero to pressure three times daily.
[b]Approximately 45 percent of minimun ultimate (virgin) burst pressure at room conditions.
[c]Vessel cycled from 0 to pressure to 0 at 2 to 5 cycles/min to failure.

TABLE VII. - EFFECT OF FIBERGLASS FINISH AND SURFACE COATING ON THE FATIGUE OF FILAMENT-WOUND FIBERGLASS PRESSURE VESSELS

[Data from ref. 3. Spherical tanks in aircraft service.]

(a) Static fatigue strength

Condition	Temperature, °F	Relative humidity, percent	Pressure,[a] psi	Time to failure, hr
Oil and starch, uncoated	120	95	4000[b]	32
Organosilane, uncoated	120	95	4000	600
Organosilane, coated[d]	120	95	4000	1324
Oil and starch, uncoated	160	95	3000[c]	158
Organosilane, uncoated	160	95	3000	1180

(b) Cyclic fatigue strength

Condition	Temperature, °F	Relative humidity, percent	Pressure,[e] psi	Number of cycles to failure
Oil and starch, uncoated	160	95	3000[c]	1 000
Organosilane, uncoated	160	95	3000	4 200
Organosilane, coated[d]	160	95	3000	13 275

[a]Vessel maintained under pressure until failure; cycled from pressure to zero to pressure three times daily.
[b]Approximately 60 percent of minimum ultimate burst pressure at room conditions.
[c]Approximately 45 percent of minimum ultimate burst pressure at room conditions.
[d]Coating unspecified.
[e]Vessel cycled from 0 to pressure to 0 at 2 to 5 cycles/min to failure.

TABLE VIII. - TIME VARIATION OF ULTIMATE BURST PRESSURE

FOR PRESSURE VESSELS EXPOSED TO 140° F AND

95 PERCENT RELATIVE HUMIDITY

DATA FROM REF. 9

Exposure time, wk (hr)	Burst pressure,[a] psi			
	As built	With proof test[b]	With proof test and sealed tube	With proof test and painted
0	3850 (3.3%)[c]	3880 (3.3%)	----	----
2 (336)	3980 (2.2%)	3480 (5.6%)	3520 (4.0%)	3700 (4.6%)
6 (1008)	3200 (4.9%)	2850 (4.4%)	----	----
16 (2688)	2780 (3.9%)	2500 (3.5%)	2750 (3.5%)	2630 (3.4%)

[a]Average value of 16 samples.
[b]Pressurized to 75 percent of unaged as-built value at 250 psi/sec with water as medium before exposure. Proof pressure reached in approximately 5 sec and held for an additional 10 sec before release.
[c]Quantity in parenthesis is coefficient of variation.

TABLE IX. - STRENGTH TESTS OF WALL SECTION OF FILAMENT-WOUND FIBERGLASS UNDERGROUND GASOLINE STORAGE TANKS

(a) Houston, Texas, tank; 6 years and 10 months continuous service (ref. 12)

Property	1964 tests[a]	1971 tests[b]
Flexural strength, psi	35.6×10^3	33.5×10^3
Flexural modulus, psi	1.50×10^6	1.83×10^6
Barcol hardness	40	48

[a]Average value.
[b]Single value.

(b) Stony Ridge, Ohio, tank; 12 years and 9 months continuous service (ref. 13)

Property	1964 tests	1977 tests
Average flexural strength, psi	26.24×10^3	27.80×10^3
Average flexural modulus, psi	1.31×10^6	1.19×10^6
Average Barcol hardness	37	35

TABLE X. - STRENGTH TESTS OF FIBERGLASS LAMINATE

HULL OF 40-FOOT PATROL BOAT (REF. 14)

[19 yr continuous service.]

Property	1962 Tests[a] (10 yr service)	1972 Tests[b] (19 yr service)
Compressive strength		
Number of samples	2	10
Average stress (range)[c], 10^3 psi	12.20 (3.20)	12.21 (1.82)
Shear strength		
Number of samples	3	10
Average stress (range), 10^3 psi	6.56 (1.07)	6.15 (3.01)
Flexural strength		
Number of samples	1	10
Average stress (range), 10^3 psi	9.41 (----)	10.85 (2.15)
Tensile strength		
Number of samples	1	10
Average stress (range), 10^3 psi	5.99 (----)	6.14 (2.5)

[a]Sample from one location on bottom.
[b]Sample from two locations on bottom.
[c]Values in parenthesis indicate range of variation from minimum to maximum values for the number of samples tested.

TABLE XI. - PROPERTY TESTS OF GLASS REINFORCED PLASTIC PANELS FROM FAIRWATER OF SUBMARINE U.S.S. HALFBEAK (REF. 15)

[11 yr service.]

Property	Condition	Original[a] data (1954)	1965 data		
			1st panel	2nd panel	Average
Flexural strength, psi	Dry Wet[b]	52 400 54 300	51 900 46 400	51 900 47 300	51 900 46 900
Flexural modulus, $x10^{-6}$, psi	Dry Wet	2.54 2.49	2.62 2.45	2.41 2.28	2.52 2.37
Compressive strength, psi	Dry Wet	---- ----	40 200 35 900	38 000 35 200	39 100 35 600
Barcol hardness	Dry	55	53	50	52
Specific gravity	Dry	1.68	1.69	1.66	1.68
Resin content, percent	Dry	47.6	47.4	48.2	47.8

[a]Average of three panels.
[b]Specimen boiled for 2 hr and then cooled at room temperature for 1 hr prior to testing.

TABLE XII. - TENSILE AND FLEXURAL TESTS OF FIBERGLASS ROTODOME OF GRUMMAN E-2A AIRCRAFT (REF. 16)

[19 yr exposure: several in flight service, rest in outdoor storage.]

(a) Flexural strength

Specimen area	Stress, psi, $\times 10^{-3}$		Modulus, psi, $\times 10^{-6}$	
	Original (1958)	Aged (1978)	Original (1958)	Aged (1978)
Upper skin, paint on	61.5	53.8	----	----
	63.5	56.8	----	----
	63.5	57.0	----	----
Average	62.2	55.9		
Bottom skin, paint on	64.0	76.4	2.75	2.34
	57.5	65.9	2.30	2.37
	62.0	76.4	2.50	2.37
Average	61.2	72.9	2.52	2.36
Upper skin, paint off	63.0	57.2	1.9	1.88
	66.0	59.6	2.0	1.88
	67.3	59.9	2.1	1.90
Average	65.9	58.9	2.0	1.89
Inner skin, no paint	61.5	53.5	1.8	1.36
	59.0	56.8	1.9	1.45
Moisture content, 1.1 percent	60.0	57.3	1.7	1.63
Average	60.2	55.9	1.8	1.48
Cap, paint off (eroded) Moisture, 0.84 percent	65.0	43.9	----	----

(b) Tensile strength

Specimen area	Stress, psi, $\times 10^{-3}$		Modulus, psi, $\times 10^{-6}$	
	Original (1959)	Aged (1978)	Original (1959)	Aged (1978)
Bottom skin, paint on	32.0	37.2	2.1	2.07
	32.0	25.3	1.7	1.98
	31.5	34.4	2.2	1.94
Moisture content, 1.32 percent	36.5	35.1	2.3	1.89
	36.5	37.8	2.3	1.88
Average	33.7	34.0	2.1	1.95
Upper skin, paint on	36.3	39.5	2.3	1.83
	39.4	42.9	2.5	2.09
Moisture content, 1.46 percent	38.9	43.9	2.6	2.27
Average	38.4	42.0	2.5	2.06
Upper skin, paint off	37.0	35.0	2.5	1.77
	40.0	34.0	2.8	1.88
	39.0	38.5	2.5	1.94
Moisture content, 1.00 percent	40.0	32.2	2.5	1.74
	40.0	38.5	2.7	1.98
Average	39.0	35.7	2.6	1.86

[a]Values normalized to nominal ply thickness of 0.011 in. at 25° C.

TABLE XIII. - TENSILE AND FLEXURAL TESTS OF FIBERGLASS NOSE RADOMES OF GRUMMAN A-6 AIRCRAFT (REF. 16)[a]

[11 to 15 yr flight service.]

Resin		Date in service	Resin content, percent	Moisture content, percent	Tensile stress, psi, x10^{-3}		Flexural stress, psi, x10^{-3}		Flexural modulus, psi, x10^{-6}	
Type	Serial number				Original	Aged	Original	Aged	Original	Aged
828/BF_3-400	38	5-63	16.6	0.50	80.5	75.8	68.9	38.9	2.25	3.13
828/MNA/BDMA	195	9-65	17.1	0.20	93.8	94.7	88.9	87.1	3.14	4.00
	266	4-66	17.7	.20	88.1	88.0	86.3	82.5	2.64	3.05
	299	10-66	16.7	.18	87.4	89.5	91.3	86.0	3.16	3.13
	369	4-67	16.6	.25	91.0	89.5	80.2	96.1	3.00	----

[a]Average of five samples each at 25° C.

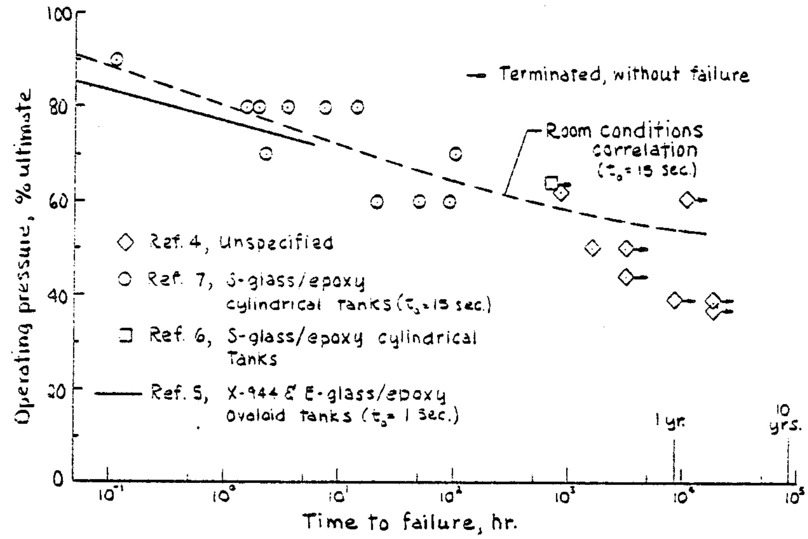


Figure 1.- Static fatigue of uncoated fiberglass-reinforced filament-wound pressure vessels. Small-scale laboratory & production samples.

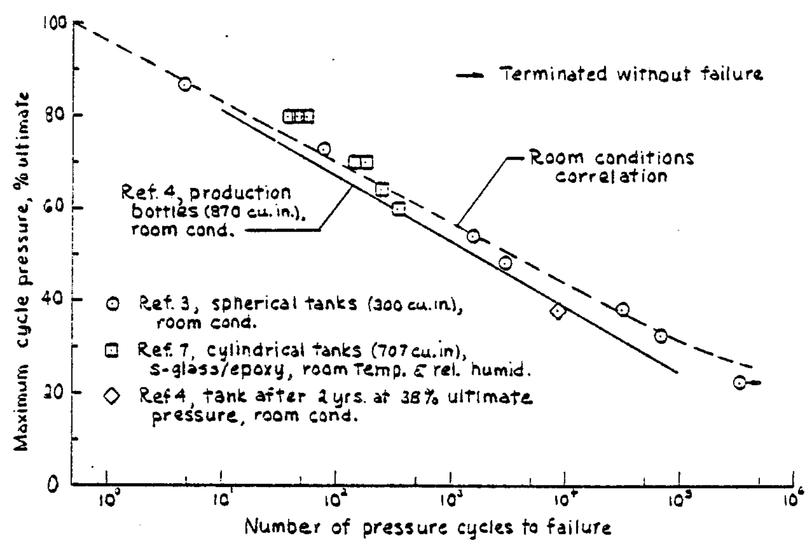
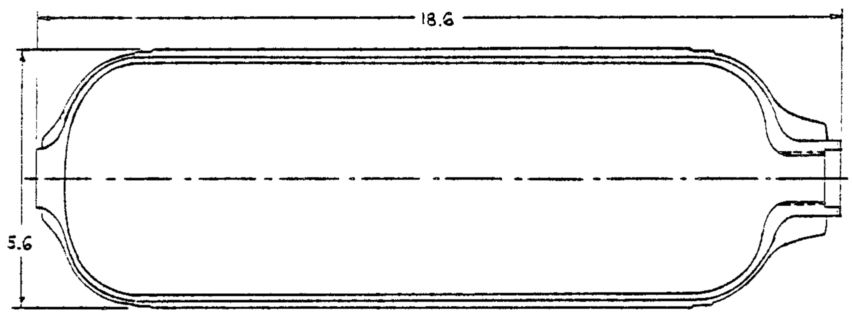


Figure 2.- Cyclic fatigue of uncoated, fiberglass-reinforced, filament-wound pressure vessels. Small-scale laboratory and production samples.



Liner: 6070-T6 Aluminum (seamless); 0.122 wall thickness

Overwrap: Fiberglass/epoxy composite
S-2 glass fiber
Epon 828/103/NMA/BDMA resin system

Operating pressure: 4,500 psig at 70°F

Figure 3.– Fireman's portable air storage tank for compressed-air breathing system. Martin Marietta Corp. (ref. 8). Dimensions in inches.

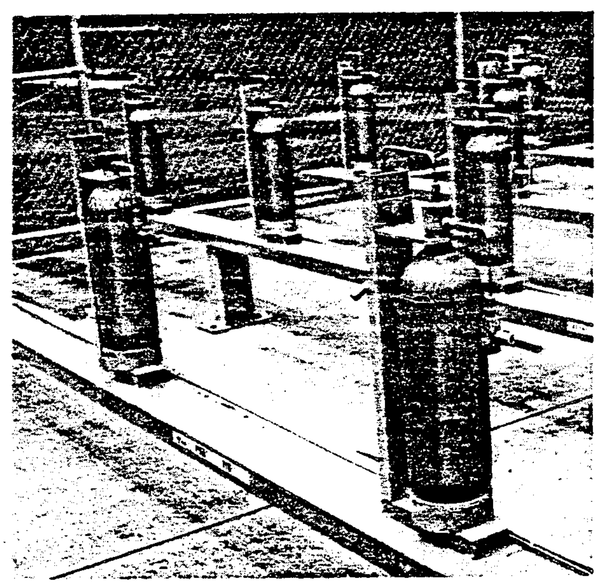


Figure 4. - Outdoor tank pressurization farm at NASA-Lewis Research Center.

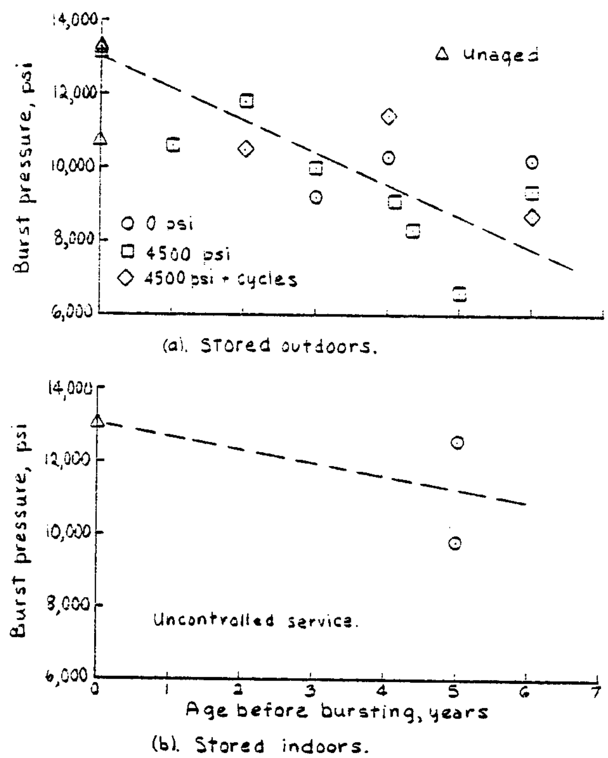


Figure 5.- Burst pressure of uncoated fiberglass-reinforced plastic storage tanks. S-2 glass/epoxy overwrap on aluminum liner (table III). NASA-LeRC tests.

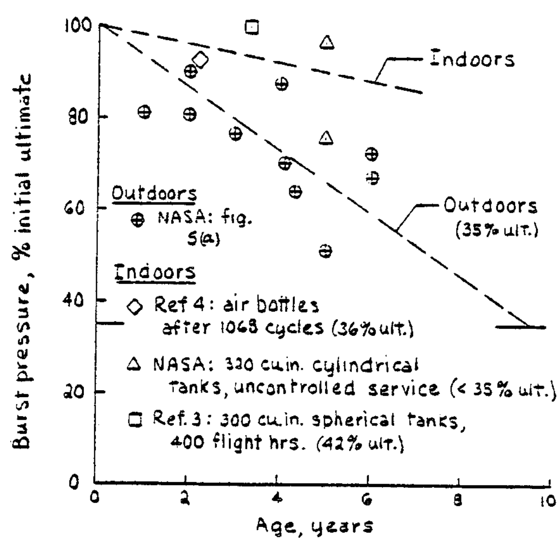
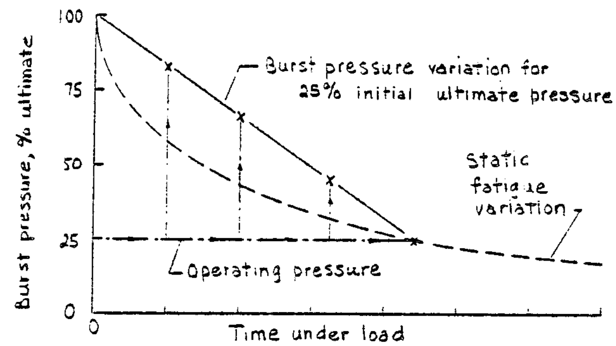
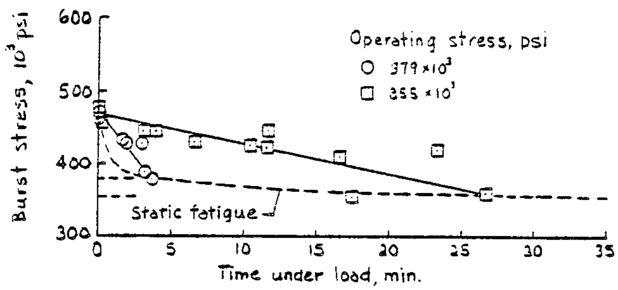


Figure 6.- Estimated correlation for burst strength of uncoated filament-wound pressure vessels. Room test conditions; operating pressure in percent of initial ultimate value in parenthesis.

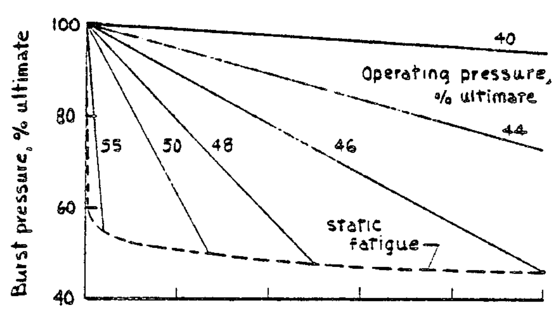


(a). Schematic represention of burst pressure variation.

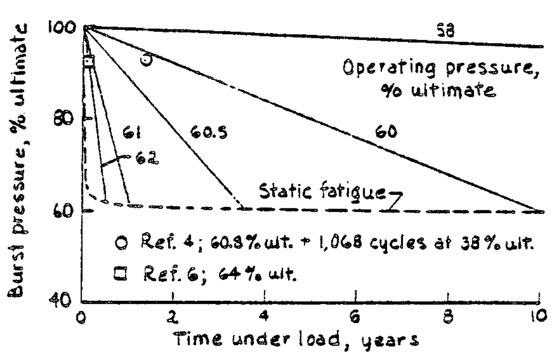


(b). Experimental variation of glass fiber burst strength under rapid loading. Data from reference 5.

Figure 7.- Relationship between burst strength and static fatigue strength for fiberglass pressure vessels.



(a). Low extrapolation.



(b) High extrapolation.

Figure 8.— Estimated burst pressure variations for different extrapolations of static fatigue data of figure 1 for indoor conditions.

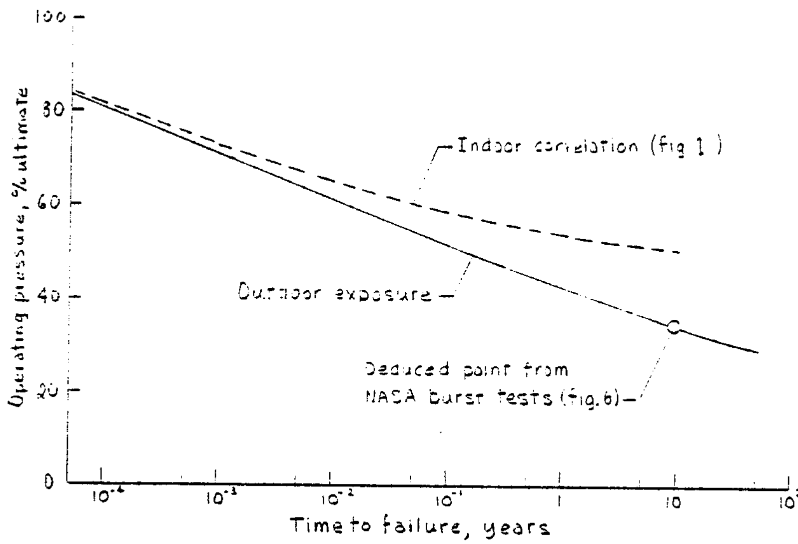


Figure 9.-Estimated static fatigue of uncoated, fiberglass-reinforced, filament-wound pressure vessels under outdoor exposure.

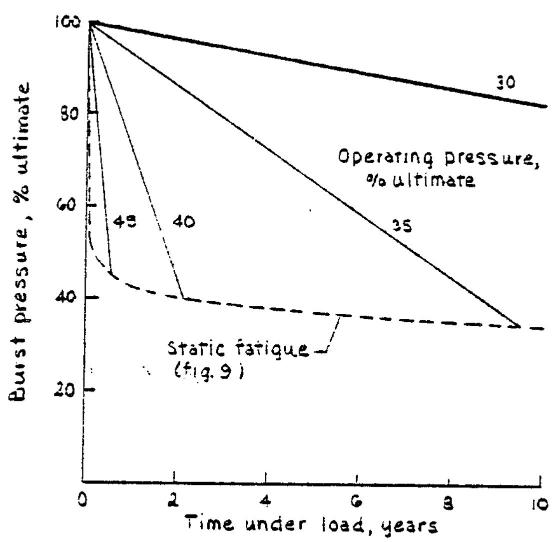
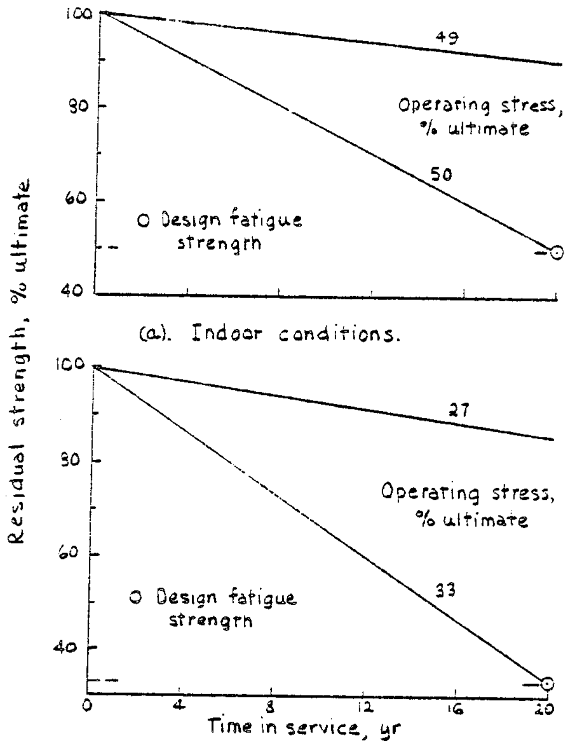


Figure 10.-Estimated burst pressure variations for uncoated filament-wound pressure vessels under outdoor exposure.



(b). Outdoor conditions.

Figure 11.- Illustration of construction of estimated residual strength variations for fiberglass pressure vessels based on static fatigue correlations of figure 7.

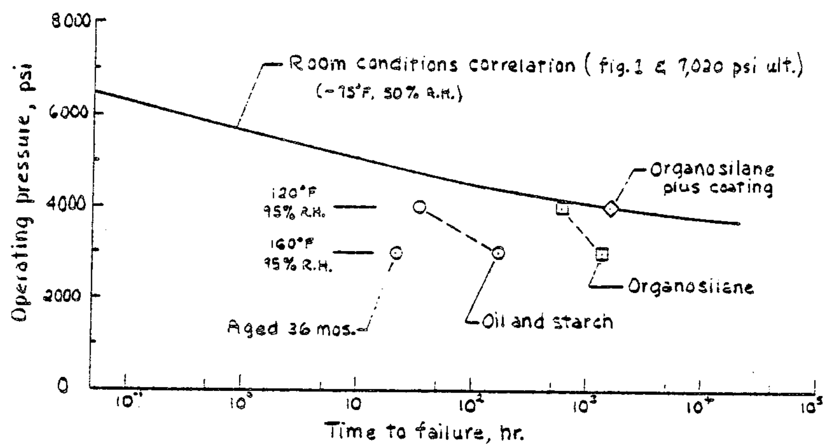


Figure 12.- Effect of moisture, temperature, and fiberglass finish on static fatigue of spherical pressure vessels. Data from ref. 3.

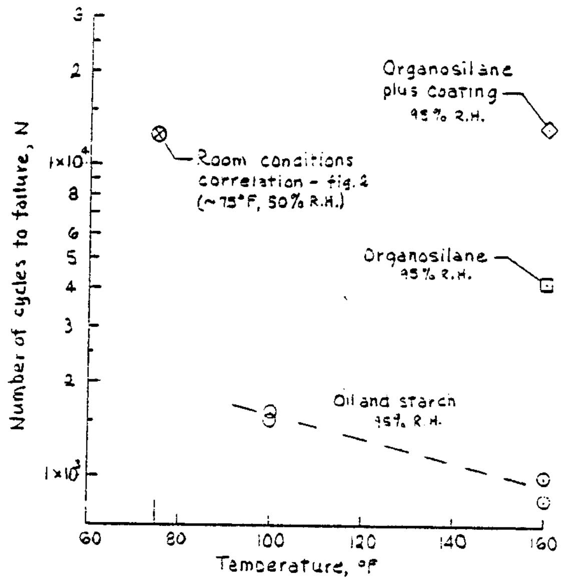


Figure 13.- Effect of moisture, temperature and fiberglass finish on cyclic fatigue of spherical pressure vessels. Operating pressure, 3000 psi (42.7 % ultimate). Data from ref. 3.

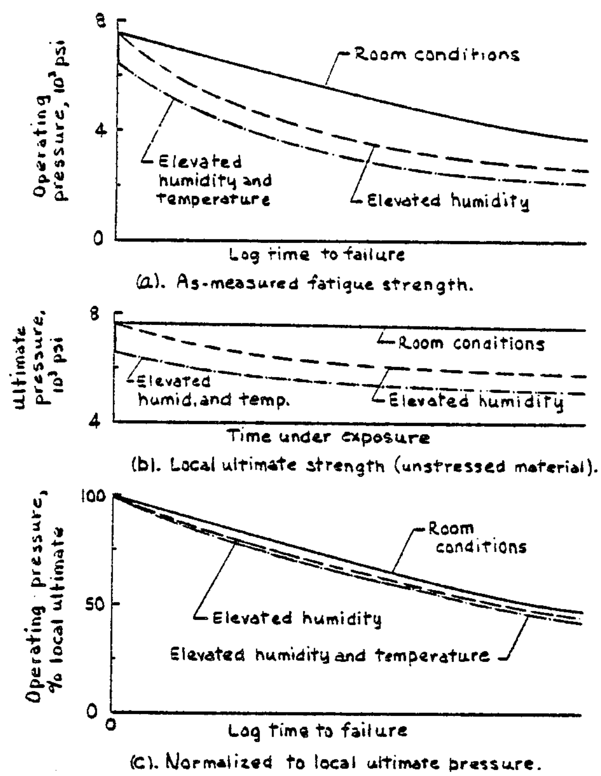


Figure 14.- Schematic illustration of static fatigue strength components for pressure vessel exposed to high moisture environment.

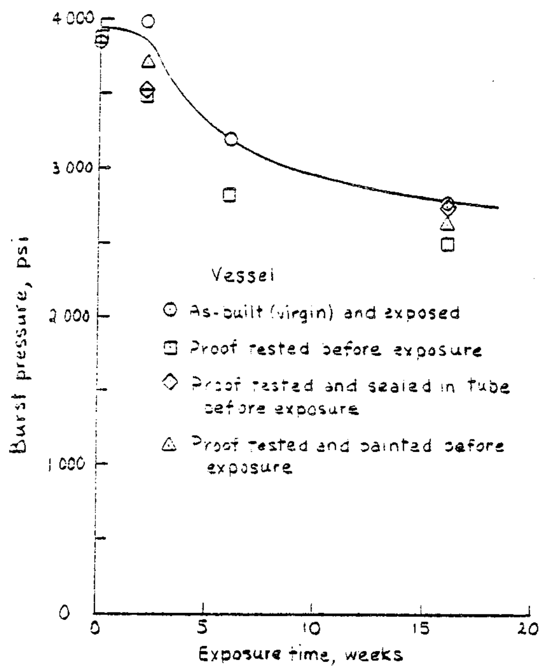


Figure 15.- Variation of ultimate (no-load) burst strength with exposure to 140°F and 95% relative humidity for 3-in. diameter, glass/epoxy, filament-wound pressure vessels unpressurized during exposure (from ref. 9).

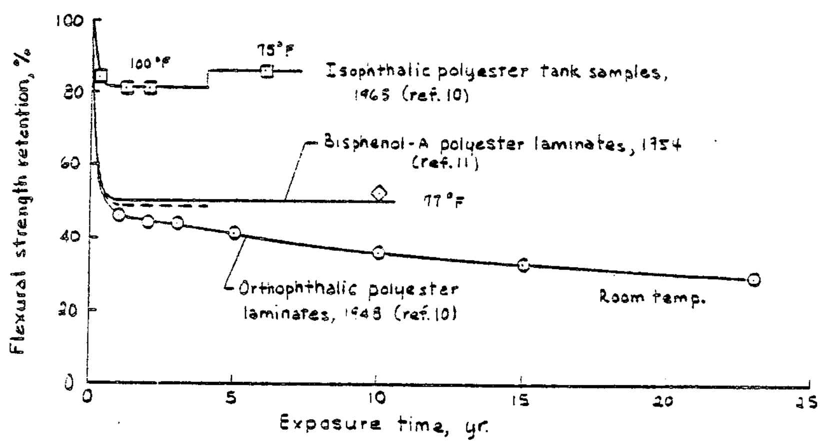


Figure 16. - Variation of flexural strength retention with time of exposure to water for fiberglass/polyester resin laminates for petroleum fuel tank use.

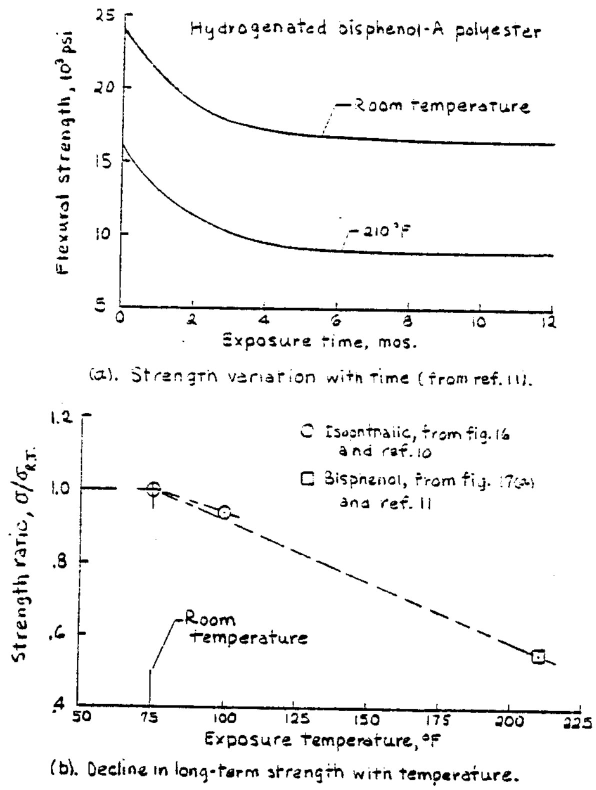
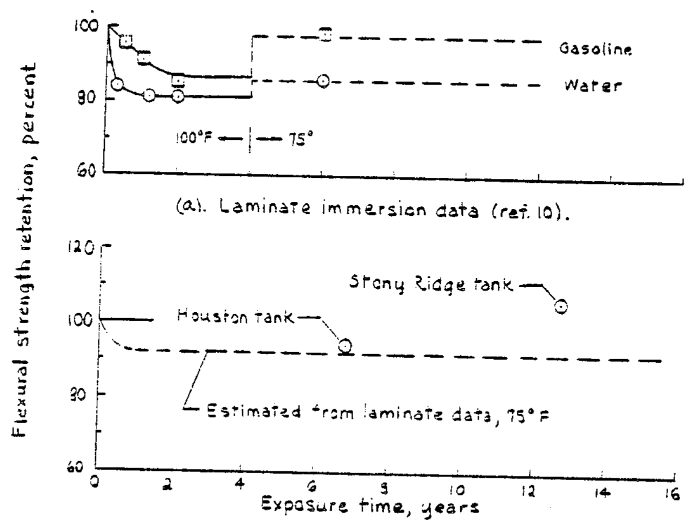


Figure 17.- Effect of exposure temperature on strength of unstressed polyester resin laminates immersed in water.

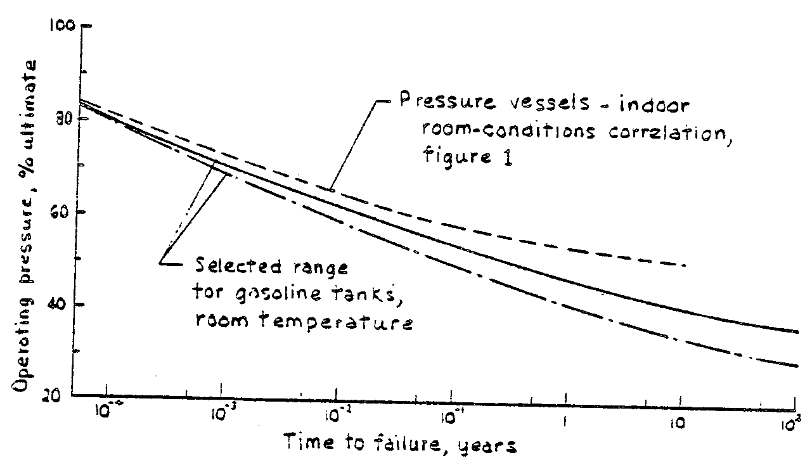
Figure 18. - Filament-wound fiberglass gasoline storage tank unearthed after $12\frac{3}{4}$ years of service. (Photo courtesy of Owens-Corning Fiberglas Corp.)



(a). Laminate immersion data (ref. 10).

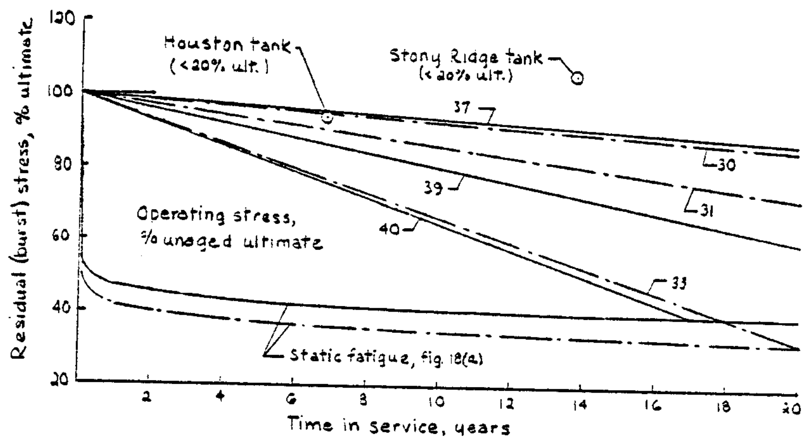
(b). Service tank data (refs. 12 and 13).

Figure 19.- Flexural strength retention for filament-wound fiberglass underground gasoline storage tanks.



(a). Estimate of static fatigue strength variation.

Figure 20.- Estimated residual strength variation for underground gasoline storage tanks as pressure vessels.



(b). Residual (burst) stress variation at room temperature.

Figure 20.- Concluded.

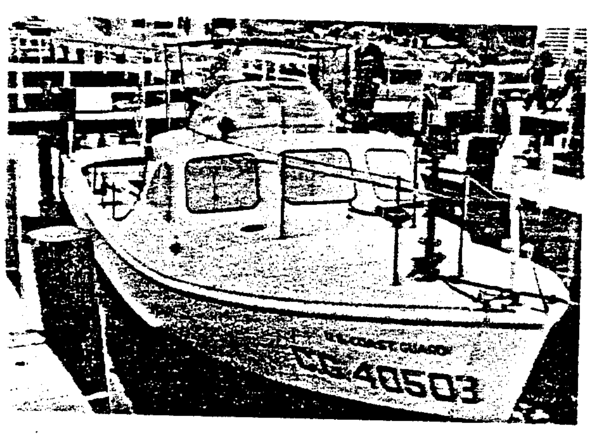
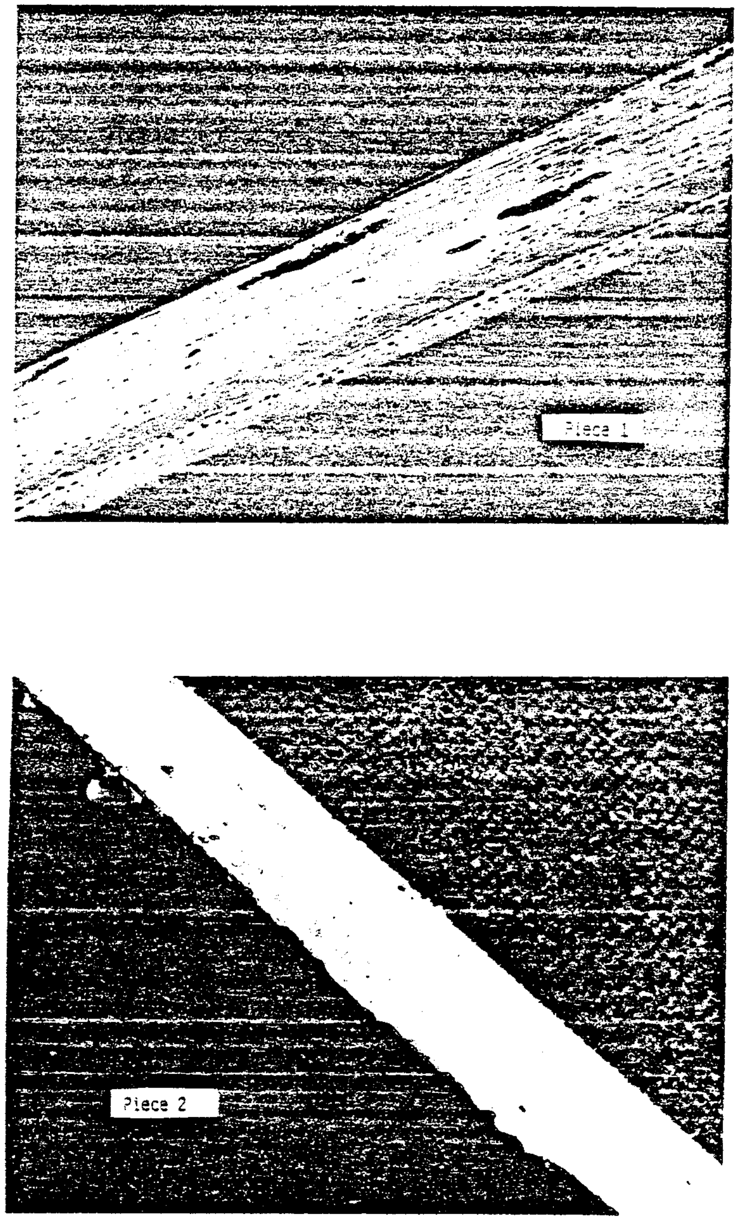
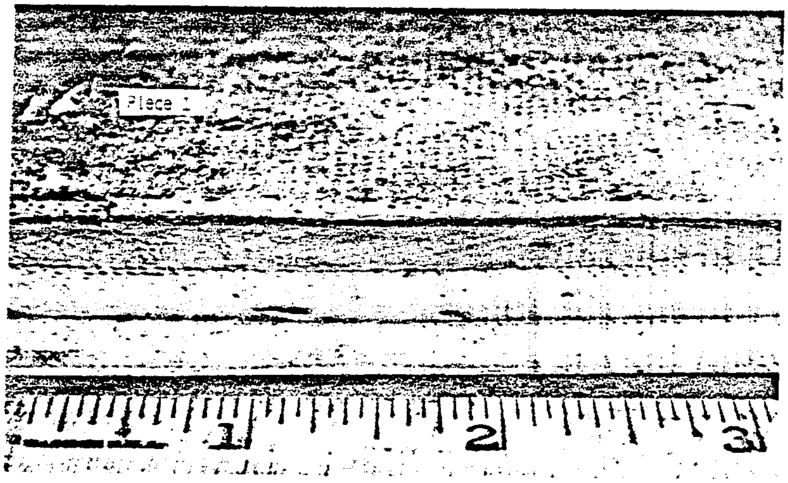


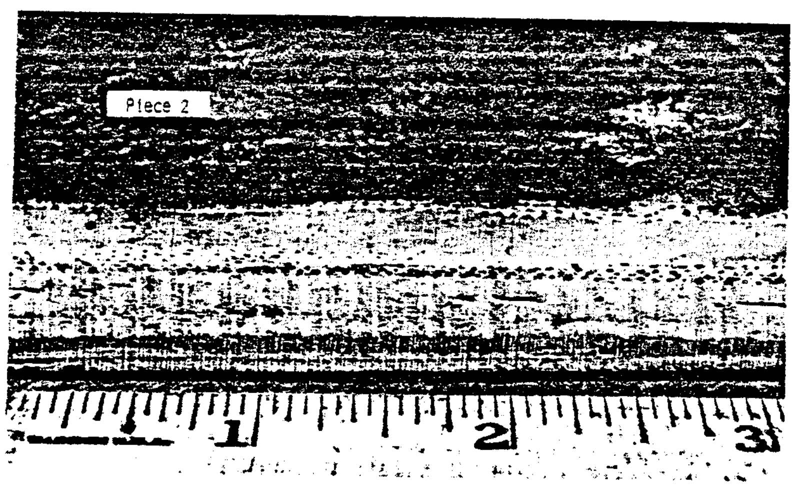
Figure 21. - 40-Foot Coast Guard patrol boat with fiberglass hull. (Photo courtesy of Owens-Corning Fiberglas Corp.)



(a) Laminate sections, 1962.

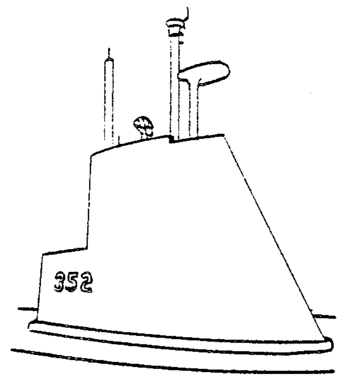
Figure 22. - Cross sections of hull laminates of Coast Guard patrol boat after 10 and 19 years of continuous service. (Photo courtesy of Owens-Corning Fiberglas Corp.)



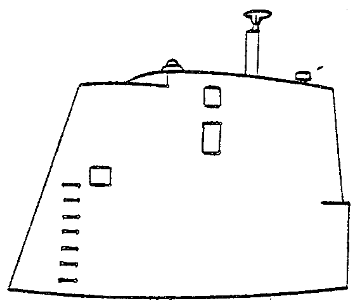


(b) Laminate sections, 1971.

Figure 22. - Concluded.

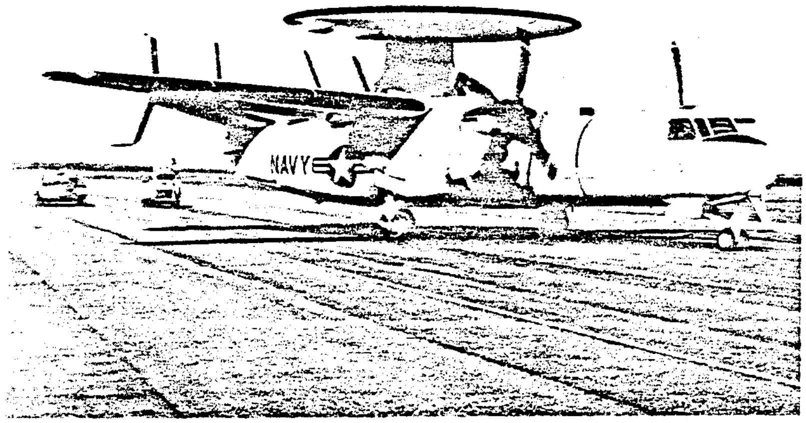


(a). Fairwater on USS Halfbeak.

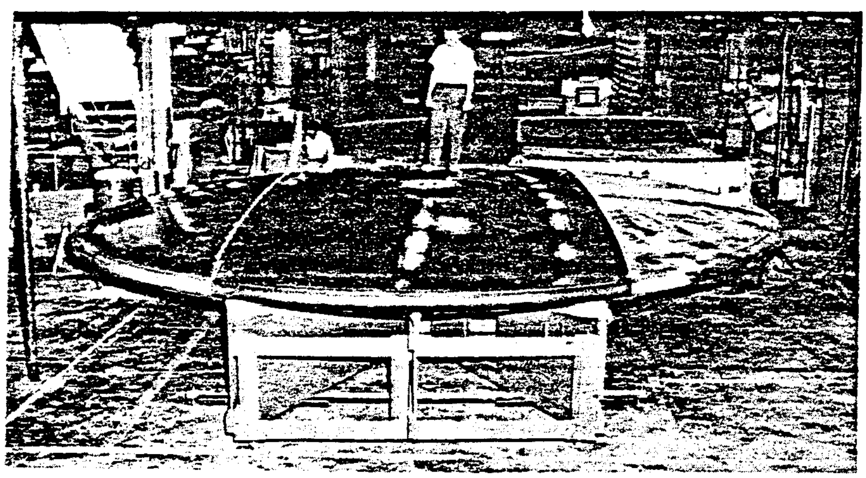


(b). Typical "high-bridge" fairwater.

Figure 23.- Glass-reinforced plastic fairwaters instal-
on submarines (ref. 15).

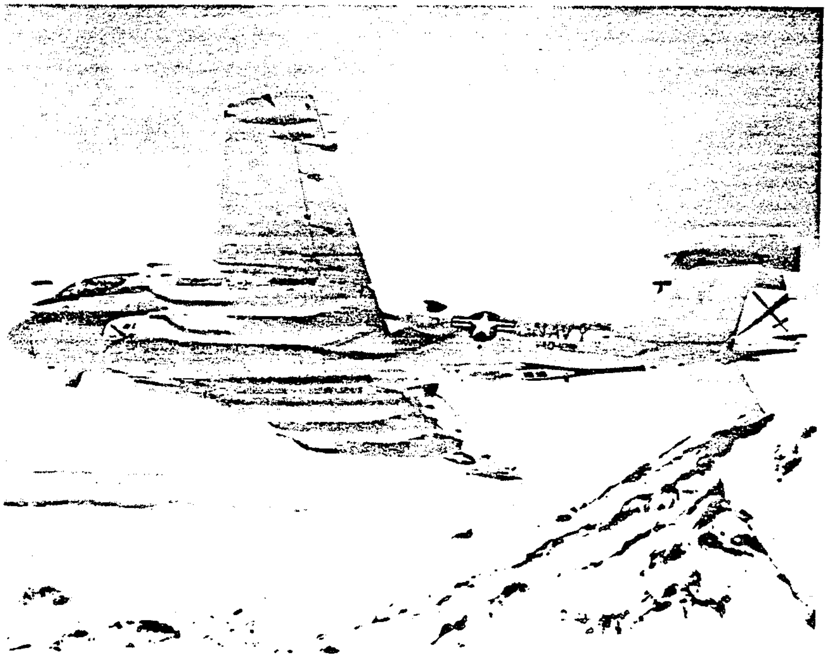


(a) Aircraft.

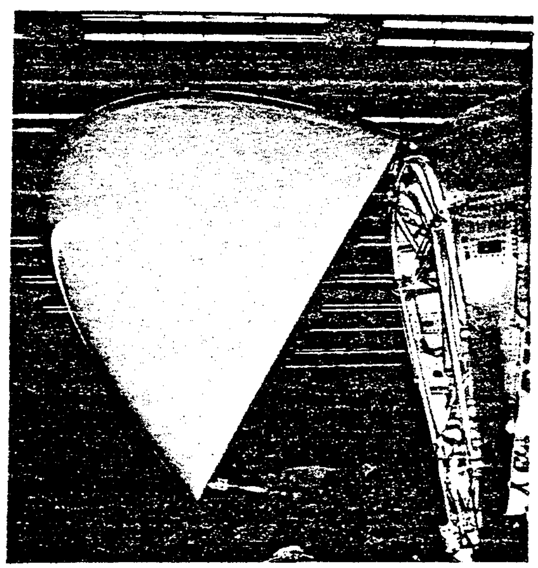


(b) Close-up view of rotodome.

Figure 24. - Fiberglass laminate rotodome installed on Grumman E-2A aircraft. (Photo courtesy of Grumman Aerospace Corp.)

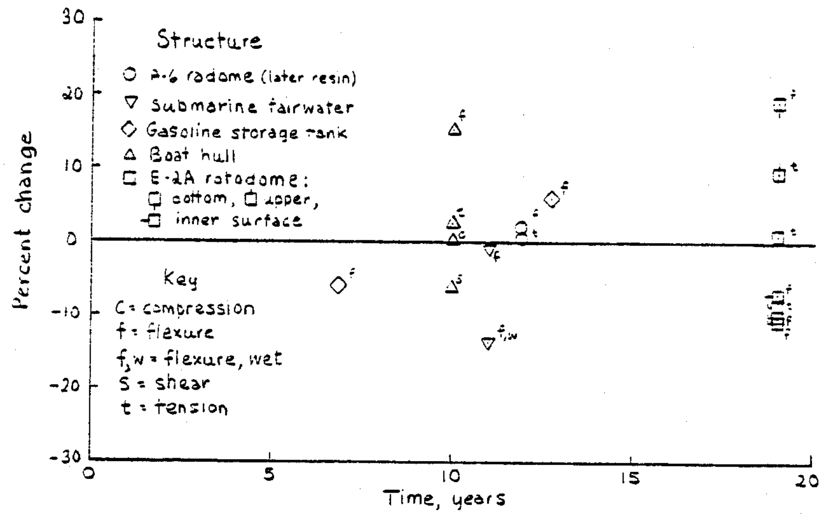


(a) Aircraft.



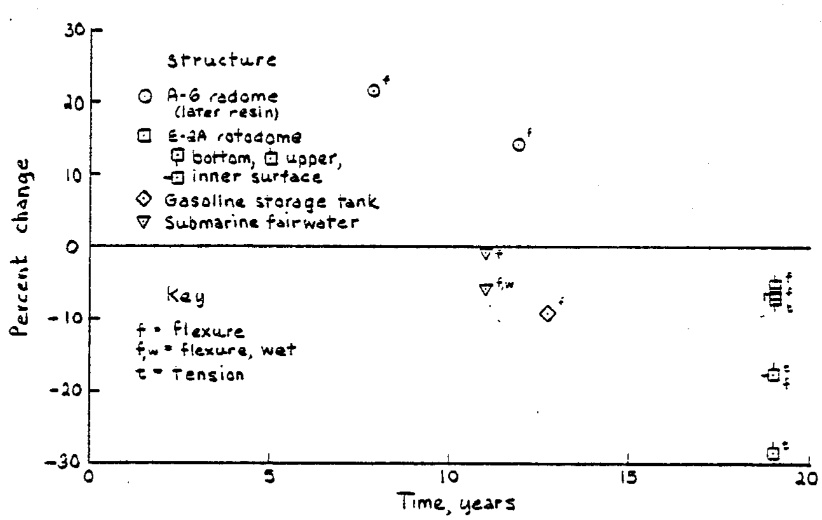
(b) Close-up view of radome.

Figure 25. - Filament-wound fiberglass nose radome on Grumman A-6 aircraft. (Photo courtesy of Grumman Aerospace Corp.)



(a). Strength.

Figure 26.-Average values of change in static properties of full-scale fiberglass reinforced structures.



(b). Modulus.

Figure 26.-Concluded.